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SOLAR RADIO CONTINUUM STORMS AND A  
"BREATHING" MAGNETIC FIELD MODEL

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## CONTENTS

	<u>Page No.</u>
Abstract .....	1
1. Introduction .....	3
2. Properties of Radio Continuum Storms .....	7
3. Relation to Type III Burst Storms .....	15
4. Emission Mechanisms .....	18
5. Possible Magnetic Configuration of Radio Continuum Sources .....	23
6. Generation and Storage Mechanisms of Energetic Electrons Responsible for the Storms .....	26
7. "Breathing" Magnetic Field Model .....	29
8. Concluding Remarks .....	34
References .....	36
Caption of Figures .....	40

## Abstract

Radio noise continuum emissions observed in metric and decametric wave frequencies are, in general, associated with actively varying sunspot groups accompanied by the S-component of microwave radio emissions. It is known that these continuum emission sources, often called type I storm sources, are often associated with type III burst storm activity from metric to hectometric wave frequencies. This storm activity is, therefore, closely connected with the development of these continuum emission sources.

It is shown that the S-component emission in microwave frequencies generally precedes by several days before the emission of these noise continuum storms of lower frequencies. In order for these storms to develop, the growth of sunspot groups into complex types is very important in addition to the increase of the average magnetic field intensity and area of these groups. In particular, the types of these groups such as  $\beta\gamma$  and  $\gamma$  are very important on the generation of noise continuum storm sources and sharp increase of the flux of these continuum emissions. This fact suggests that sunspot magnetic configuration and its variation, both space and time, are very effective on these noise continuum emissions.

Although we have not known yet the true mechanism of these emissions, it is very likely that energetic electrons, 10 to 100 Kev, accelerated in association with the variation of sunspot magnetic fields, are identified as the sources of those radio emissions. Furthermore, these electrons are now considered as explicable to the emission of type III burst storms associated with the noise

continuum storm sources. In explaining these storms, some plasma processes must be taken into consideration. Furthermore, it should be remarked that the storage mechanism of the electrons mentioned above plays an important role in explaining the relation of the noise continuum emissions and type III burst storms, because "on-fringe" type III bursts are all generated above these noise continuum storm sources. After giving a review on the theory of these noise continuum storm emissions, a model is briefly considered to explain the relation just mentioned, and a discussion is given on the role of energetic electrons on the emissions of both noise continuum and type III burst storms. It is pointed out that instabilities associated with these electrons and their relation to their own stabilizing effects are important in interpreting both of these storms.

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## 1. Introduction

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Radio noise continuum storms, sometimes called type I noise storms, were first observed by Hey in February and March, 1942 (see Hey, 1946; Appleton and Hey, 1946). In his book on the historical review of the development of radio astronomy, he has described the story of his discovery of these continuums (Hey, 1972). During the period mentioned above, a large sunspot group in the northern hemisphere, accompanying these continuums, was very active and produced solar proton flares twice, from which Bev-energy particles were ejected on 28 February and 7 March (see Lange and Forbush, 1942; Forbush, 1946).

Since the end of World War II, the Australian group, headed by Bolton, initiated the research on solar radio astronomy with galactic radio astronomy. Based on the early research results, Wild (1951, 1957) proposed a classification system on various aspects and characteristics of solar radio emissions, which mainly defines three groups of characteristic radio emissions, called the bursts of spectral types I, II, and III. The radio noise continuums observed by Hey are classified as type I burst storms, although the characteristics of these storms were sometimes considered to be different from isolated bursts of type I (see Pawsey and Smerd, 1953; Wild, 1957). However, it is very likely that these bursts are produced as a result of superposition of many type I burst emissions, since the observed characteristics of these bursts are very similar to those of

type I bursts (e.g., Kundu, 1965; Zheleznyakov, 1970).

As well known, these noise continuum storm sources are generally associated with sunspot groups fully developed as classified to the E and F types (Fokker, 1960, 1965). The characteristics of these storms and their relation to the passage of associated active sunspot groups were first investigated by Boischot (1958) using the observational results from the Nancey interferometer at 169 MHz. His results indicate that these sources are usually associated with sunspot groups well-developed, and that they are located somewhere above or close to these groups. In this case, it should be noted that, because of their narrow emission directivity, the flux intensity from these radio sources is not high while they are located near the limb of the solar disk (see Fokker, 1965).

Recent observations at Culgoora, Australia, at both 80 and 160 MHz show that these noise continuum storms are generally of composites of two oppositely polarized sources usually located adjacent to each other (Kai, 1970; Wild, 1970; Kai and Sheridan, 1973). The polarization of these sources well reflects the direction of sunspot magnetic fields ambient in these sources. Furthermore, the observational results suggest that these noise continuum storms are generated by some mechanism related to plasma processes since the emission region of these two frequencies (e.g., Kai and Sheridan, 1973; Dulk and Nelson, 1973). Although we have not known yet what mechanism can generate these noise storms, it is very likely that energetic electrons of 10 - 100 Kev are mainly responsible for the excitation of plasma waves, which is transformed into electromagnetic waves due to some non-linear plasma processes as discussed by Ginzburg and Zheleznyakov

(1958), Takakura (1963), Trakhtengerts (1966) and Tsytovich (1966), 1967). This idea has been sophisticated by theoretical works of Melrose (1970 a, b) and Smith (1970 a, b, 1972, 1973), a relation to their consideration on type III bursts.

It seems that the formation of energetic electron beams and their instability due to the interaction with ambient plasmas play a very important role in generating noise continuum storms. Although this formation seems to be closely related to energization mechanism of ambient electrons and the processes of bunching accelerated electrons, it is certain that this energization occurs independently from solar flare activity, as shown by Fokker (1965). However, our recent results suggest that efficient generation of energetic electrons is closely tied up with the growth of associated sunspot groups into complex types such as  $\beta\gamma$  and  $\gamma$  (Sakurai, 1974). This suggests that these electrons are accelerated as a result of instabilities associated with sunspot magnetic configurations.

The emission bandwidth of these noise continuum storms was first thought as limited to very narrow one such as 10 MHz wide (e.g., Kundu, 1965). However, recent observations show that the emission frequencies of these storms are often extended into decametric frequencies (e.g., Warwick, 1965) and sometimes farther into hectometric frequencies (e.g., Fainberg and Stone, 1971), although these narrow-band characters seem to be maintained with respect to each observed frequency. These observations, therefore, suggest that energetic electrons are ejected high up into the solar corona by exciting plasma waves which are determined by the distribution of the density of the electrons ambient in the outer solar corona. In this case, it seems important to point out that the same electron beams are

possibly responsible for the generation of such wide-band continuum emission from metric to hectometric wave frequencies (e. g., Sakurai, 1973).

In this paper, a review is given on various problems as discussed above with the aim to summarize the current status on the research for solar radio continuum emissions from metric to hectometric wave frequencies. In so doing, the role of energetic electrons is extensively considered in relation to the mechanism of these continuum emissions. A theoretical model is briefly considered to interpret the observational characteristics of these emissions.



## 2. Properties of Radio Continuum Storms

In order to study the development of these radio noise continuum storms, it is necessary to find out young active regions which have become active in these storm emissions since they were newly born on the visible disk within fifty degrees east in solar longitude. If not so, it is impossible to study how these storm sources are developed in association with the growth of active sunspot groups and other associated phenomena. Since these sunspot groups are generally accompanied by flares and other active phenomena, it is possible to study the relation of the noise continuum storms with these active phenomena. In particular, it is interesting to find out how these storms are related to other radio phenomena such as the S-component of microwave emissions in their developmental phase; it seems that the S-component emissions are causatively related to the development of these noise storm sources (e.g., Kai and Sekiguchi, 1973).

We here pick up the solar radio phenomena observed during the period from 3 to 15 May, 1971 in order to study the relation mentioned above in association with the development of the active region MacMath No. 11294. This active region became active in the emission of noise continuum storms in metric and decametric wave frequencies on 6th of May. The activity of this emission sharply increased on 7th of this month, one day after the beginning of this emission (see Fig. 1). In Fig. 1, we show the daily flux values of both metric continuum (200 MHz) and S-component (2800 MHz) emissions. These data are obtained from

the Quarterly Bulletin of Solar Activity (1971). The result shown in this figure indicates that the sharp increase of the metric continuum flux is delayed about a day from that of the S-component flux. It should be remarked that this sharp increase shown in Fig. 1 is accompanied by the very high activity on type III bursts in decametric frequencies (Gergely, 1974). Furthermore, it is interesting to note that this sharp increase also seemed to be related to the growth of the sunspot group into the  $\beta\gamma$  type, which is the one of very complex configuration of these groups (Fig. 1). In fact, as shown in Fig. 2, the flux intensity of metric continuum storm emissions tends to sharply increase just after associated sunspot groups become the complex configurations like  $\beta\gamma$  type. In this figure, we show two cases associated with the sunspot groups MacMath Nos. 11294 and 12094. The latter was observed on the solar disk for 18 to 30 of October, 1971. Its developmental pattern of radio emission activity in both metric and microwave frequencies is almost the same as that of the region MacMath No. 11294. As clearly seen in Fig. 2, the sharp increase of metric continuum storm emission tends to occur just after an associated sunspot group becomes the configuration of  $\beta\gamma$  type. It is also clear that, for first several days, the activity of metric noise continuum storm is very low and almost constant, while the activity of microwave S-component emission tends to increase very sharply (Fig. 2). This fact suggests that the growth of the sources for the S-component emissions is very important for the birth of the source of metric noise continuums.

In order to find out the statistical relation between the developments of both metric continuum and microwave S-component emissions, it seems reasonable to study the time delay from the maximum activity of S-component

emissions to that of metric noise continuum emissions by taking into account the daily flux values for both these emissions. These time delays are analyzed for the period 1969-1972 and are indicated in Fig. 3. This result shows that the maximum flux intensity of metric continuum emissions is mainly reached within a day after the S-component emissions attain maximum. This suggests that the growth of the source of S-component emissions is considered as an important precursor of the development of metric noise continuum storms. Furthermore, it may be said that the birth and growth of metric continuum storm sources is closely associated with these of microwave S-component emissions; that is, metric continuum sources do not grow independently from microwave S-component sources, though such independence was once suggested (see Fokker, 1965).

The result shown in Fig. 3, further, suggests that the growth of the sources for microwave S-component emission tends to induce that of metric noise continuum sources. This relation was once suggested by Kai and Sekiguchi (1973), but our result shown above indicates that the change of sunspot groups into complex types is very important in forming metric noise continuum storm sources. Gergely (1974) has found that type III burst activity at decametric wave frequencies associated with metric noise continuum emissions was highest on 7th of May 1971, although this activity was observed between 3rd and 13th of this month. This activity is schematically shown in Fig. 4. During this period, the IMP-6 satellite was also observing solar radio emissions, and detected many type III bursts in hectometric and kilometric wave frequencies. Although the data obtained by this satellite were not good in quality during the period from 7 to 9 of May, we

may say that the type III burst activity in these low frequencies was delayed by a few days in comparison with this activity in decametric wave frequencies (Fig. 4). This delay may be related to the further growth of the sunspot group MacMath No. 11294 during its passage over the solar disk. As suggested by Kai and Sekiguchi (1973), this delay may be explained by considering an outward expansion motion of sunspot magnetic field lines of arch-like configuration, since the field intensity and background plasma density are both decreased with this motion. In fact, this arch-like configuration extending farther out, was deduced by Gergely (1974). This configuration calculated by Trotter et al (1973) was here indicated in Fig. 5. The sources of radio emissions with wide-band frequencies from microwave to decametric waves, really speaking, were all confined in this extended arch-like structure of sunspot magnetic fields. The sources for type III bursts, especially, "on-fringe" type III bursts were located above this structure (Gergely, 1974).

As shown in Fig. 2, it is clear that the activity of metric noise continuum sources sharply increases when the type of associated sunspot groups grows into complex types as  $\beta\gamma$  and  $\gamma$ . Fokker (1965) analyzed the relation between sunspot types and the activity of these sources and found that the sunspot groups classified as E and F types (the Zürich Classification) are most active on the formation of these radio sources. In the analysis of the metric continuum noise storm sources observed in July to August, 1967, which was associated with the active region MacMath No. 8905, Sakurai (1971 a) found that the development of the storm source was not related to the flare activity associated with this active region. These

results, therefore, suggest that the generation of the energetic electrons (10 - 100 Kev) responsible for those radio emissions is independent from flare activity (Sakurai, 1971 a).

The relation of the low-frequency continuum storms with energetic electron stream detected at the earth's orbit was first shown by Sakurai (1973) on the observations for the period October to November, 1968. This result suggests that these electron streams are responsible for the excitation of radio noise continuum storms from metric to hectometric wave frequencies. Similar observation was made for the period 10 - 26 August, 1968 (Fainberg and Stone, 1970, 1971; Sakurai, 1971 b). The changing patterns of both metric and hectometric continuum storm emissions were very similar for these two cases cited above. We examined the IMP-6 satellite records to find out some evidence on the continuum emissions in low frequencies during the period from 3 to 14 May, 1971. However, we did not see any trend on the increase of background continuum storm emissions in these frequencies. Although it seems that the active regions on metric noise continuum storm emissions tend to be accompanied by the sources of hectometric continuum storms (Stone and Fainberg, 1973; Fainberg and Stone, 1974), it seems natural that these continuum storms are not often observed because of diverging tendency of these sources, which is closely associated with an expansive nature of sunspot magnetic field lines above active regions.

Radio waves emitted from the sources of these noise continuum storms are usually polarized in circular modes. It seems that the modes of polarization are strongly dependent on the distribution of sunspot magnetic fields identified as these sources. Using the data obtained by the Culgoora radio heliograph, Kai and

Sheridan (1973) have proposed a model on the source structure of noise continuum storm emissions in two discrete wave frequencies (80 and 160 MHz). According to them, this structure is very important in explaining the observed features on polarization, both L-H and R-H waves, since these two polarization modes can be explained by taking into account the polarity distribution of sunspot magnetic fields accompanying these radio sources. Several years ago, Kai (1970) found that there exist double sources of these noise continuum emissions above sunspot groups, which are usually oppositely polarized, as schematically described in Fig. 6. The results obtained by Kai and Sheridan (1973) also show that double sources, oppositely polarized from each other, were observed. However, one of these sources is sometimes missing as found by Dulk and Nelson (1973). Their result indicates that this kind of absence may occur in accordance with the configuration of associated sunspot magnetic fields.

Fig. 6 schematically shows that energetic electrons released from noise continuum source regions are mainly transported along magnetic field lines radially extending outward of these regions. These electrons seem to be identified as sources of type III burst storms (Kai, 1970). These burst storms may be identified as the "on-fringe" burst storms as found by Gergely (1974), for the highest emission frequencies of these bursts are expected to be generally lower than the lowest emission frequencies of noise continuum emissions.

Fainberg and Stone (1970) found that, in August 1968, type III burst storm in low frequencies was observed in association with the passage of the active region MacMath No. 9597. In this period, the activity of decametric continuum

emissions also was very high (Sakurai, 1971 b). It seems that these type III burst storms were produced by the passage of Kev electron streams in the outer corona and the envelope of the sun. In fact, these streams were observed during 20 to 23 in August, 1968 while the active region mentioned above was on the western hemisphere, though the electron flux was not high (Lin, private communication, 1970). As shown in Fig. 6, it seems that the electron streams released from the noise storm regions tend to move mainly along the neutral sheet which forms above the active regions (Wild and Weiss, 1964; Sakurai and Stone, 1971). Since it seems unlikely that this sheet is maintained in the region far away from the active region, say more than 20 solar radii from the sun, it may be almost impossible to detect these electrons in any sector boundary observed at the earth's orbit. In this respect, however, it should be noted that these electrons are well controlled by the interplanetary magnetic field lines during their propagation (e.g., Lin, 1970; Fainberg and Stone, 1974).

At present, noise continuum storm emissions and type III burst storms are thought to be generated by energetic electrons due to their interaction with ambient plasmas. In particular, the noise continuum storms are generated by the electron streams continually emitted from the sun (Sakurai, 1971 b, 1973). A clear evidence has been shown in the period between 20 October and 4 November, 1968; the time variation of Kev electrons fluxes ( $\geq 22$  and  $\geq 45$  Kev) observed at the earth's orbit was very similar to those of the noise continuum storm fluxes at metric and hectometric wave frequencies. A similar evidence, though not much clear, was found in August, 1968 (Sakurai, 1971 b; Stone and Fainberg, 1973).

These evidences are important in considering theory to explain the emission mechanism of noise continuum storms of wide-band frequencies.



### 3. Relation to Type III Burst Storms

Gergely (1974) has found that type III burst activity at decametric wave frequencies was very high while the active region MacMath No. 11294 was on transit over the solar disk. This activity indicates that many type III bursts were consecutively superposed and then may be said to be type III burst storms. The highest activity of this burst storm associated with the active region mentioned above was observed on 7 May, 1971 when the type of the associated sunspot group changed to the  $\beta\gamma$  type (see the discussion in last chapter).

This sort of type III burst activity in hectometric wave frequencies was first discovered by Fainberg and Stone (1971), based on the analysis of the observational data from the RAE-A satellite. We here show one of the results obtained by them in Fig. 7. In this figure, the data on metric continuum storm emissions at 200 MHz, observed at Hiraiso, Japan, is also shown. These two results in both metric and hectometric wave frequencies indicate that the changing patterns of the radio fluxes in the two frequencies are very similar to each other except for small-scale variations in time. Furthermore, the results shown in Fig. 7 suggests that the same source responsible for metric noise continuum storm emissions was extended into the outer corona around 10 to 20 solar radii away from the sun. During the period shown in Fig. 7, we also observed continuum storms in decametric wave frequencies, 10 ~ 60 MHz, the data of which were obtained at Boulder, Colorado (Malitson, 1969; see also, Sakurai, 1971 b). These continuum emissions, classified as type I noise continuum

storm, are explained as a composite of many type III and type I bursts superposed on type I continuum storms. Since these bursts are continually emitted, they seem to be really observed as if continuum storm emissions were generated in the active region. However, this problem is not finally solved yet.

The relation between this type of noise continuum storm and type III bursts has been investigated by several authors (e.g., Malville, 1962; Hanasz, 1966; Wild and Tlamicha, 1964; Gordon, 1970; Gergely, 1974). The analyzed results indicate that the starting frequencies of the emission of type III bursts, which are classified as the "on-fringe" bursts (Gergely, 1974), is usually lower than the lowest emission frequencies of (Type I) noise continuum storms. In fact, these "on-fringe" type III bursts are generated directly above associated active sunspot complexes (see Gergely, 1974).

In August, 1968, the noise continuum storm source was observed as shown in Fig. 7 and associated with low-frequency continuum storm (0.54 - 2.8 MHz), which seemed to be located higher up in the solar outer corona beyond 10 solar radii or more from the sun (Fainberg and Stone, 1970). This continuum storm was connected with a noise continuum storm (e.g., type I noise storm) in the frequency range from metric to decametric waves as discussed here before (see Fig. 7 (b)). In order to interpret this connection with these noise continuum storm sources widely separated from each other, Sakurai (1971 b) and Stewart and Labrum (1972) have considered models of associated active regions and the configuration of magnetic fields extended out of these active regions. Both of

them discussed the relation between these low-frequency continuum storms and type I noise sources observed in metric and decametric wave frequencies. Stewart et al (1972) have given a detailed discussion on this connection by referring to the radio data obtained by the Culgoora radio-heliograph.

Since the time of the CMP of the noise continuum source at hectometric wave frequencies was delayed by about one day from that of the active region associated with the noise continuum source at metric wave frequencies (Fainberg and Stone, 1970), it is concluded that the former source was not formed radially above the latter source; this fact suggests that the source structure was tilted eastward with the elevation of the radio source from the solar surface into the solar outer corona.

In the case of the radio noise activity in May, 1971, the type III burst activity in hectometric wave frequencies was observed by the IMP-6 satellite (Sakurai, 1974). As shown by Gergely (1974), this activity in decametric wave frequencies was observed during 4 to 14 of May. The highest activity was found on 7th of this month, but this activity in hectometric wave frequencies was very low on this day. In fact, the increase of this activity was found a few days after 7th, and reached maximum around 9 and 10 of May. Such delay may have been resulted from the expanding motion of the associated active sunspot groups, although we need to examine many more events similar to that which has been cited here.

#### 4. Emission Mechanism

As discussed in the last two chapters, Kev-energy electrons generated in active sunspot groups must be the sources of radio continuum storm emissions for wide frequency bands. These electrons seem to excite plasma oscillations in the medium, through which they are passing. It is noted that the frequency of these oscillations is expressed as

$$\omega^2 = \omega_p^2 + \frac{3kT}{m} K^2, \quad (4-1)$$

when the oscillations are excited in thermal plasmas. Here,  $\omega$ ,  $\omega_p$ ,  $k$ ,  $T$  and  $m$  are, respectively, the wave and the plasma frequencies, the Boltzmann constant, the temperature and the mass of electron.  $K$  is the wave number of plasma oscillations. Since these oscillations consist of longitudinal waves only, it turns out that some mechanism must be found on the transformation from these waves to transverse waves, identified as electromagnetic waves, which are emitted into outer space. Although many theories have been proposed until now to find out this mechanism, we may say that the fundamental process has first been discovered by Ginzburg and Zheleznyakov (1958, 1961). This process takes into account the scattering of those longitudinal waves on the polarization clouds of ions, i.e., electron density fluctuation, and is described as

$$p + i \longrightarrow t + i^1, \quad (4-2)$$

where  $p$ ,  $t$ ,  $i$  and  $i^1$  are, respectively, the longitudinal plasma waves, the transverse (electromagnetic) waves and the polarization clouds of ions before and after the

collision with the longitudinal waves. In this interaction, there is a possibility for the transverse waves to be amplified as far as this interaction continues in the medium (Smith, 1970 a, 1973).

We may, further, consider the emission mechanism of the second harmonic of transverse waves by taking into account the following interaction:

$$p + p \longrightarrow t (2 \omega p). \quad (4-3)$$

However, this process does not seem important in the theory of radio noise continuum storm emissions, although this process is applied to explain the second harmonic observed in type III radio bursts (e.g., Kundu, 1965; Smith, 1970 a).

In the processes as described in eq. (4-2), we assume that Kev electron streams excite plasma waves oscillating with wave frequencies given by eq. (4-1). As first pointed out by Sturrock (1964), these plasma waves thus generated tend to grow without limit and then produce the two stream instability in the parent electron beams. Generally speaking, these beams are, therefore, not maintained stably while moving in the medium like the solar outer corona. In fact, this instability is very serious in the theory of type III radio bursts (see Smith, 1970 a, b; Melrose, 1970 a, b; Papadopoulos et al, 1974). In case of radio continuum noise storm emissions, this instability may be useful to explain the dispersive nature and other characteristics of these emissions. Takakura (1963) first found that the observed short duration of these emissions could be explained by taking into this instability associated with the electron beams, though not clearly mentioned. The cause of this observed short duration seems to be closely

associated with the instability observed on the electron beams or bunches if we refer to the theoretical results by Melrose (1970 a).

It is well known that radio noise continuum storm sources are usually associated with type III burst activity observed above these sources (see the discussions in the last chapter). As shown by Malville (1962) and Gergely (1974), the starting emission frequencies of type III bursts (e.g., "on-fringe" bursts) are generally lower than the lowest frequencies of associated noise continuum storm emissions. Since these bursts are mainly observed in the regions where sunspot magnetic field lines are distributed almost radially in direction, the configuration of these field lines may have some effects on the stabilization of electron beams released from the noise continuum source regions. As shown in Fig. 5, these continuum sources are usually confined in the sunspot magnetic fields with arch-like configuration (Gergely, 1974). The contrast of magnetic field structures between continuum storm source regions and the regions in which "on-fringe" type III bursts are generated, must be considered in investigating the emission mechanisms of both noise continuums and type III bursts.

So far many theories have been proposed to interpret these mechanisms, but none has considered the effect of ambient magnetic fields on the stability of electron beams in the solar atmosphere above sunspot active regions, because of theoretical difficulty to include this effect. As considered by Gordon (1970), the stabilization of electron beams may be dependent on plasma parameters in the region where plasma waves are excited, but the contrast mentioned above seems to give us a clue to find out some mechanism to stabilize the beams under

the action of ambient sunspot magnetic fields.

It is known that type III burst storms are usually observed in the regions above active sunspot groups associated with radio noise continuum storms in metric or/and decametric wave frequencies (see the discussion in the last chapter). Furthermore, it is now believed that the energetic electrons responsible for the emission of type III bursts are released from the regions where radio noise storms are generated for these electrons are continually produced in active sunspot groups. Although we do not know how these electrons are released from noise storm source regions, it seems likely that they are ejected out of these storm source regions as a result of rapid variation of associated sunspot magnetic field lines. As shown in Fig. 1, type III burst activity was sharply increased when the type of associated sunspot group grew into the complex type classified as  $\beta\gamma$ . This result suggests that both efficiencies of generation of energetic electrons and of their release are highly dependent on the growth of associated sunspot groups.

The energetic electrons released from noise continuum storm regions seem to propagate outward along sunspot magnetic field lines radially extending into the outer solar corona. While propagating, they would excite plasma waves with frequencies given by eq. (4-1). As discussed earlier in this chapter, these waves are transformed into electromagnetic waves which are emitted as type III bursts into outer space. Most of energetic electrons, being trapped by sunspot magnetic field lines with arch-like configuration, are identified as the sources of

noise continuum storms in metric and decametric wave frequencies. Therefore, these sources usually form double source structures, the polarization of which is opposite from each other (e.g., Kai, 1970; Kai and Sheridan, 1973; Wild, 1970) (see Fig. 6).



It has been shown in Figs. 5 and 6 that radio continuum noise storm sources are usually accompanied by magnetically active sunspot regions. Above these regions, magnetic field lines generally consist of bipolar type configuration, though very complicated. In fact, the activity in these continuum emissions usually tends to increase when associated sunspot magnetic configurations change into such types as  $\beta \gamma$  and  $\gamma$ . This fact suggests that magnetic configuration above sunspot groups is very important in generating the condition favorable to the occurrence of these noise continuum emissions in the solar corona, although this condition is clearly dependent on the efficiency on the generation of energetic electrons of Kev energy (e.g., 10 - 100 Kev).

In order that these electrons are well confined in the region above associated sunspot groups must not be opened into infinity, but closed somewhere in the solar corona or envelope. If these field lines were opened, all electrons generated in sunspot groups would be soon released into outer space and therefore, no radio noise continuum storm sources would be formed above sunspot groups. Since such closed field lines are able to confine charged particles, though slowly releasing due to their drift motion (Benz and Gold, 1971; Newkirk, 1973), it may be said that the magnetic configuration associated with noise continuum sources are usually similar to those shown in Figs. 5 and 6. However, it should be remarked that any simple configuration of bipolar type sunspot magnetic fields is not useful to explain efficient generation of Kev electrons in sunspot groups, because this configuration is not appropriate to the onset of instability effective to electron acceleration. As indicated in Fig. 1, the activity of metric noise continuum emission was highly

intensified immediately after the configuration of the sunspot magnetic fields, for instance MacMath No. 11294, changed into the  $\beta\gamma$  type. This result suggests that this type of complex configuration is very efficient to the generation of Kev electrons.

It may be, however, mentioned that the region where Kev electrons are generated, is not identified as that where radio noise continuum emissions are produced, even if they are both located in the solar coronal region. It seems that the former is closely connected with observable sunspot groups because Kev electrons seem to be generated deep in the solar atmosphere in association with some instability of sunspot magnetic fields which are indirectly seen as the change of sunspot magnetic fields into some complex types as  $\beta\gamma$  and  $\gamma$ . As shown in Fig. 5, radio continuum sources are generally formed in the region where extended sunspot magnetic field lines are closed with an arch-like configuration. The results obtained by Gergely (1974) indicate that almost all the cases have such magnetic configurations as shown in Fig. 5. Several models proposed thus far also show that the configuration shown in this figure is most plausible to explain the development of radio noise continuum storm sources (see Kai, 1970; Wilcox, 1968; Sakurai and Stone, 1971; Sakurai, 1971 a, b; Daignes et al, 1971; Kai and Sheridan, 1973; Dulk and Nelson, 1973; Stewart and Labrum, 1972). However, it must be remarked that there exist two distinct types of these radio sources with respect to both the extension of arch-like magnetic configurations into the solar corona and the electron density distribution associated with these configurations (Gergely, 1974). Highly densed plasma regions extended into the

solar corona are usually associated with the largely extended arch-like magnetic configurations accompanying radio noise continuum storms and vice versa. As indicated by Gergely (1974), in general, newly-born active radio continuum sources are, however, accompanied by far-extended regions with high background electron density concentration into the solar corona. This fact suggests that, as suggested in Chapter 2, arch-like sunspot magnetic field lines tend to generally extend outward through the coronal region after newly born while trapping energetic electrons generated below. This explanation is consistent with that proposed by Kai and Sekiguchi (1973). Sakurai (1974) has also considered the possibility as an important step on the development of radio noise continuum storms in metric and decametric wave frequencies.

## 6. Generation and Storage Mechanisms of Energetic Electrons Responsible for The Storms

It has already been mentioned that both radio noise continuum storms and associated type III radio bursts are generated by some plasma processes being excited by the streams of Kev electrons passing through the background plasma medium in the solar coronal region. At the present moment, we do not know any emission mechanism independent from the role of these energetic electrons in the solar corona. As shown by Sakurai (1971 b, 1973), the continuous streams of Kev electrons from radio continuum storm sources were sometimes observed by means of satellites at the earth's orbit. In fact, the time variation of the electron flux was very similar to that of radio continuum flux in hectometric wave frequencies or higher during October to November, 1968. This sort of observation gives us an important clue to find out the emission mechanism of these continuum storms, because these storms are generally accompanied by enhanced activity of type III burst storms (Fainberg and Stone, 1971, 1974).

As we have described in Chapter 2, the development of radio continuum storm sources are usually preceded by that of the sources of microwave S-component emissions. Since the S-component emissions are also generated by energetic electrons (10 - 100 Kev), although the emission mechanisms are not the same as that of radio continuum storms in metric wave frequencies or less, the generation of these electrons is, therefore, very important in explaining steady components of radio emissions associated with the growth of magnetically active sunspot regions.

In order to explain radio noise continuum storms with respect to their emission, we, therefore, have to consider the role of these electrons based on the consideration of electron beam-plasma interaction in the solar corona. In so doing, we first consider the acceleration processes of these electrons independent from observable solar flare activity. These processes have been considered by several authors in relation to the origin of radio continuum noise storm emissions in metric and decametric wave frequencies (e.g., Takakura, 1963; Fokker, 1965; Trakhtengerts, 1966; Sakurai, 1967, 1971 b; Gordon, 1970). It seems that the interaction of thermal-tail electrons with plasma waves generated by some microinstability in ambient plasmas produces energetic electrons (Takakura, 1967; Gordon, 1970). Such instability seems to be continually produced in and above sunspot regions while they are rapidly growing and changing into a magnetically complex configuration. Although, at present, we do not know yet the real processes for electron acceleration in active regions, it is very certain that this acceleration is closely connected with microinstability associated with changing sunspot magnetic fields.

After acceleration to Kev energy, these electrons begin to interact with sunspot magnetic fields ambient in the region where the acceleration takes place. This interaction mainly seems to consist of diffusion process due to drifting motion of the accelerated electrons, which renders these electrons to disappear sooner or later from the acceleration regions or their neighborhood. Since it seems likely that the source regions of radio continuum emissions in metric and decametric wave frequencies are located above or close to the acceleration regions mentioned above, it is necessary to consider the storage mechanism of the accelerated

electrons after they have moved into the radio source regions observed.

As estimated by Sakurai (1967) and Kane and Lin (1972), these electrons seem to be stored in the regions where the intensity of ambient sunspot magnetic fields is 10 to 100 gauss and the background electron density is  $10^8$  to  $10^9$  per  $\text{cm}^3$ . Because of the intense magnetic fields, it seems difficult for the electrons to escape so soon from both the acceleration and the source regions by means of diffusion. Hence various processes regarding the energy loss of these electrons become important in estimating whether these electrons are fully considered as the source of noise continuum emissions under consideration. One of these processes may be considered as the mechanism of these continuum emissions. Although we are unable to estimate the energy loss rate of individual electrons for these emissions because of the lack of theory, it may be said that, as energy loss process, these emissions are one of the most important phenomena related to the behavior of these electrons in the solar corona.

It is known, as discussed in last chapter, that the configuration of sunspot magnetic fields plays a role on the formation of the sources of radio noise continuum emissions. Therefore, it seems useful to take into account this configuration as an important factor on the efficiency of storage of energetic electrons in small regions above active sunspots. In fact, we have known that, in general, the configuration of sunspot magnetic fields in the solar corona is similar to that which is shown in Fig. 5. The arch-like structure of the field lines is usually necessary for energetic electrons to be efficiently confined in order that they are the source of radio continuum storm emissions.

# 7. "Breathing" Magnetic Field Model

In this model we have a slightly fluctuating magnetic field density in a sunspot region; that is  $B = B(t)$ . This variation in magnetic field flux density creates a variation of the total pressure inside the sunspot region. This increase and decrease in pressure act like a mechanical pump that sucks electrons into the sunspot region at the base of the magnetic field from the outside region. The field then ejects the electrons along field lines into the outer corona of the sun at various levels. These ejected electrons excite the ambient plasma at these levels causing it to produce Type I radio emissions.

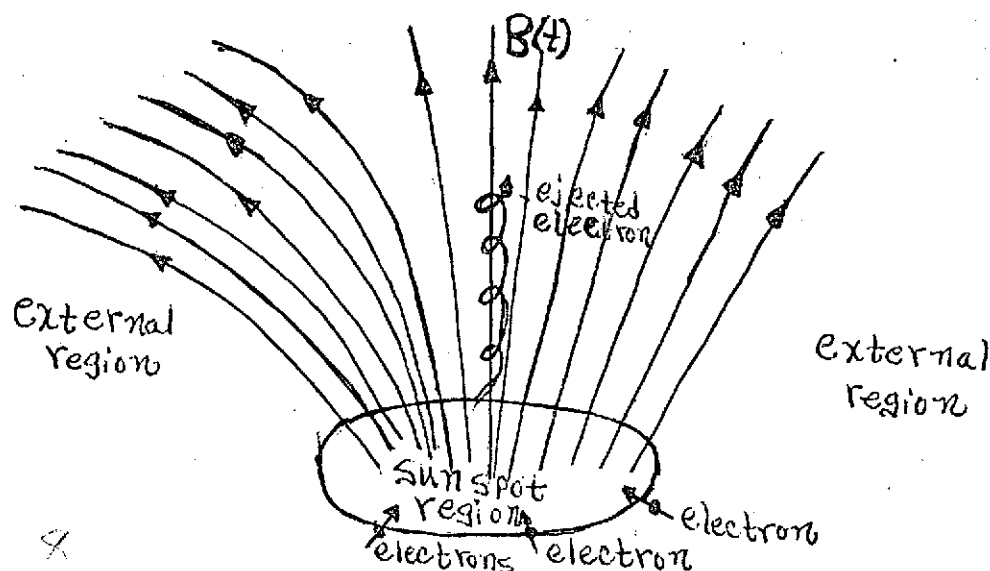


Figure 8. Diagram showing electrons entering the sunspot region at the sun's surface and then being ejected, along field lines into the outer corona.

Let us assume that at some time,  $t_0$  the magnetic field at the base of a sunspot, is  $B(t_0)$ . (Here, it should be noted that this model assumes that the magnetic flux density,  $B$ , decreases with height above the sunspot).

Also, the kinetic pressure due to the electrons inside the sun spot at  $t = t_0$  is  $P_i(t_0)$  and the kinetic pressure outside the sunspot region is  $P_o(t_0)$ . Thus, at equilibrium  $t = t_0$ ;

Where  $\mu_0$  is the permeability of free space. At sometime later  $t$ , let us assume that  $B(t_0)$  goes to  $B(t)$  where  $B(t_0) > B(t)$ . This decrease in magnetic flux density gives a total decrease in pressure inside the sunspot of an amount  $\Delta P$ , where

$$\Delta P = \frac{B(t_0)\Delta B}{\mu_0} - \frac{\Delta B^2}{2\mu_0}$$

and  $\Delta B$  is the decrease in magnetic flux density. (We have assumed that the outside region is an infinite reservoir of electrons.)

To reestablish equilibrium in pressure, additional electrons rush in from the outside region increasing the density of electrons inside the sunspot. This increase in density of electrons is found from the equation

$$\Delta P = 4n \left( \frac{1}{2} m_e v^2 \right) = 4n E_k$$

Where  $n$  is the density of additional electrons;  $\frac{1}{2} m_e v^2 = E_k$  is the kinetic energy of the electrons added to the sunspot region.



When the magnetic field returns to its original value,  $B(t)$ , to reestablish equilibrium, these additional electrons gained for a field  $B(t)$  are expelled up along the field lines where the pressure of opposition is less. The energy density gained by the electrons is given by

$$\text{Energy density} = nE_k = \frac{2B_0 \Delta B - \Delta B^2}{8\mu_0}$$

Let us now assume that the magnetic field density "over shoots" its original value  $B(t_0)$  to a value  $B(05)$ . Thus, the number of particles expelled must be greater than the original value at  $B(t)$ . Further let us assume that  $B(05)$  is of a value such that there are not enough electrons of average energy  $E_{k_0}$  to expell in order to reestablish equilibrium. Then the field must give up energy to the electrons until its energy density is low enough to reestablish equilibrium.

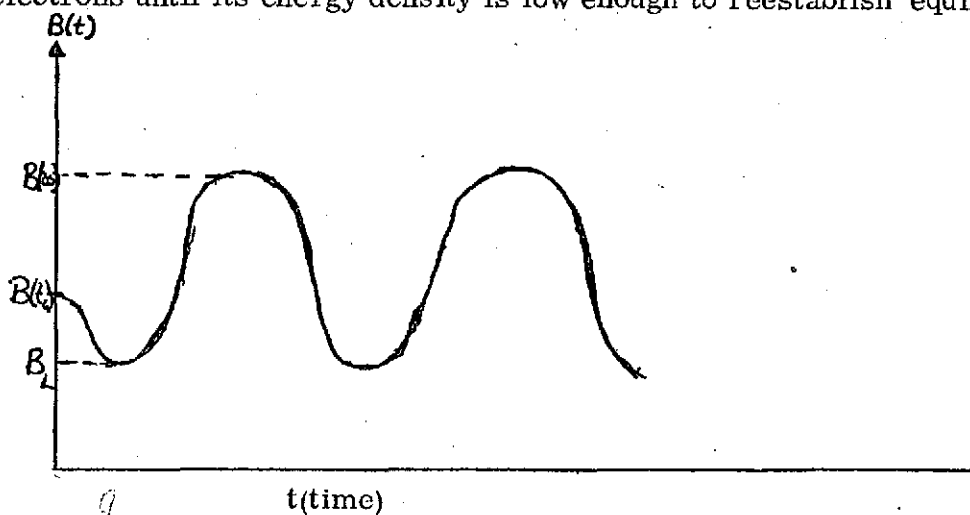


Figure 9 Graph showing the change in the magnetic field density  $B(t)$  in the sunspot as a function of time,  $t$ .

Let us now establish the energy gained by an electron on the average.

At the smallest value of  $B(t)$ ,  $B(t) = B_L$ , let the density of electrons be  $n_0$  and the average kinetic energy of an electron be  $E_{k_0}$ . Thus the energy gained by the electrons is; Since

$$\frac{B^2(0s)}{2\mu_0} > P_0 = 4n_0 E_{k_0} + \frac{B_L^2}{2\mu_0}$$

we get

$$4n_0(E_k - E_{k_0}) = \left[ \frac{B(0s)^2}{2\mu_0} + 4n_0 E_{k_0} \right] - \left[ \frac{B_L^2}{2\mu_0} + 4n_0 E_{k_0} \right]$$

[ energy density of region at B(0s) ]
[ energy density of region at  $B_L$  ]

Where  $E_k$  is the final energy of an electron. Thus

$$E_k = \frac{1}{8\mu_0 n_0} (B(0s)^2 - B_L^2) + E_{k_0}$$

At some time  $t_0$ , the sunspot has a magnetic flux density,  $B(t_0)$ . Then the field decreases to a value of  $B(t) = B_L$ . This causes electrons to rush into the sunspot region. Then the field increases to a value  $B(0s)$  large enough to give the electrons great kinetic energies when they are expelled, as the field again drops to some value below  $B(t_0)$ . This process is repeated over and over again as the field fluctuates or breathes.

Let us now make a computation with the above formula for  $E_k$ , where

$$E_k(\text{ev}) = 6.25 \times 10^9 \frac{(B^2(0s) - B_L^2)}{n_0} + E_{k_0}(\text{ev}).$$

Here  $B$  is in gauss and  $n_0$  is in electrons /cm<sup>3</sup>.

✓ If we let  $E_{k_0} = 50$  ev be the energy of the ambient plasma electrons entering the sun spot region,  $B_L = 3 \times 10^3$  gauss,  $B(0) = 3.1 \times 10^3$  gauss and  $n_0 = 10^{10}$  electrons/cm<sup>3</sup> we get

$$E_k(\text{ev}) = 6.25 \times 10^9 \frac{((3.1 \times 10^3)^2 - (3 \times 10^3)^2)}{10^{10} \frac{\text{electrons}}{\text{cm}^3}} + 50 \text{ eV}$$

$$\approx 38 \text{ KeV}.$$

This value is about the value of the energy electrons would have to have in order to excite the solar corona plasma causing it to produce the observed Type I radio emissions.

#### Special Note

The mechanism by which the transfer of magnetic field energy into kinetic energy for the electrons has not yet been developed for the model. The fundamental laws of electromagnetism are now being studied in an attempt to derive a physically feasible mechanism of energy transfer.

8. Concluding Remarks

We have considered the development of radio continuum storm sources in metric wave frequencies or less in reference to the growth of the S-component sources in microwave frequencies. In the discussion on the relation between these two sources just mentioned, we have emphasized the important role of energetic electrons of 10 - 100 Kev on the emissions of these radio waves in wide-frequency range. As described in Chapter 4, we do not know yet the mechanism of radio noise continuum emissions in metric and decametric wave frequencies, although many theories have been proposed. In this paper, in order to explain some observed characteristics, we have pointed out the importance of two-stream instability associated with energetic electron streams, although it is known that the inhibition of this instability is very important to explain the emission processes of type III radio bursts. Furthermore, it may be said that the onset of this instability is closely connected with the behavior of energetic electrons in ambient sunspot magnetic fields: that is, type III bursts are generally produced by electron streams moving along ambient sunspot magnetic field lines radially extended into the solar corona. On the other hand, the noise continuum storm emissions under discussion are produced in the sunspot magnetic fields with a configuration as shown in Fig. 5. This sort of configuration seems to be very effective on the onset of the instability associated with electron streams. On this problem, some further investigation would be necessary.

We here summarize several important problems in future investigation as follows:

34-  
-34-

- 1) The relation among radio noise continuum storms (metric or less), the S-component of microwave emissions and type III burst storms.
- 2) The emission mechanism of radio noise continuum storm.
- 3) The relation of radio noise continuum storms to solar active phenomena during their growing and decaying phases.
- 4) The generation mechanism of energetic electrons in sunspot magnetic fields actively growing.
- 5) The role of energetic electrons on the mechanism of the S-component emissions in microwave frequencies.

These problems described above seem to be important in understanding the nature of radio noise continuum storm sources in metric or lower wave frequencies. It seems that the satellite observations in hectometric and kilometric wave frequencies give us a clue to find out what mechanism is working on the emission of radio waves in these frequencies. Furthermore, these electrons would be very useful to find the mechanism of radio noise continuum storms in higher wave frequencies.

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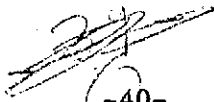
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## Caption of Figures

- Fig. 1 Intensity-time profiles of metric continuum and microwave S- component emissions (200 and 2800 MHz). The variation of sunspot activity is also shown. Type III burst activity in decametric wave frequencies has been found by Gergely (1974).
- Fig. 2 The relation between the growing activities of metric continuum and microwave S-component emissions. The same frequencies have been considered as in Fig. 1.  $\beta\gamma$  indicates the date when associated sunspot groups changed into  $\beta\gamma$  type.
- Fig. 3 The time delay of metric continuum storm activity from associated microwave S-component emissions.
- Fig. 4 Type III burst activity in both decametric and hectometric wave frequencies. For comparison, metric noise continuum activity is reproduced from Fig. 1.
- Fig. 5 The configuration of sunspot magnetic field lines associated with the active region MacMath No. 11294. A rectangle indicates the area that metric and decametric noise continuum storms were observed.
- Fig. 6 A model to explain the location of radio continuum storm sources, oppositely polarized and related sunspot magnetic fields controlling the motion of energetic electron released from these sources.

  
-40-  
-40-

**Fig. 7**      **Solar radio continuum activity observed during 10 to 26 August, 1968.**  
**(a) Metric continuum flux variation at 200 MHz, (b) Hectometric**  
**continuum storm flux variation at 1.65 MHz observed by the RAE-A**  
**satellite.**

Solar Activity Associated with Active Region  
MacMath No. 11294

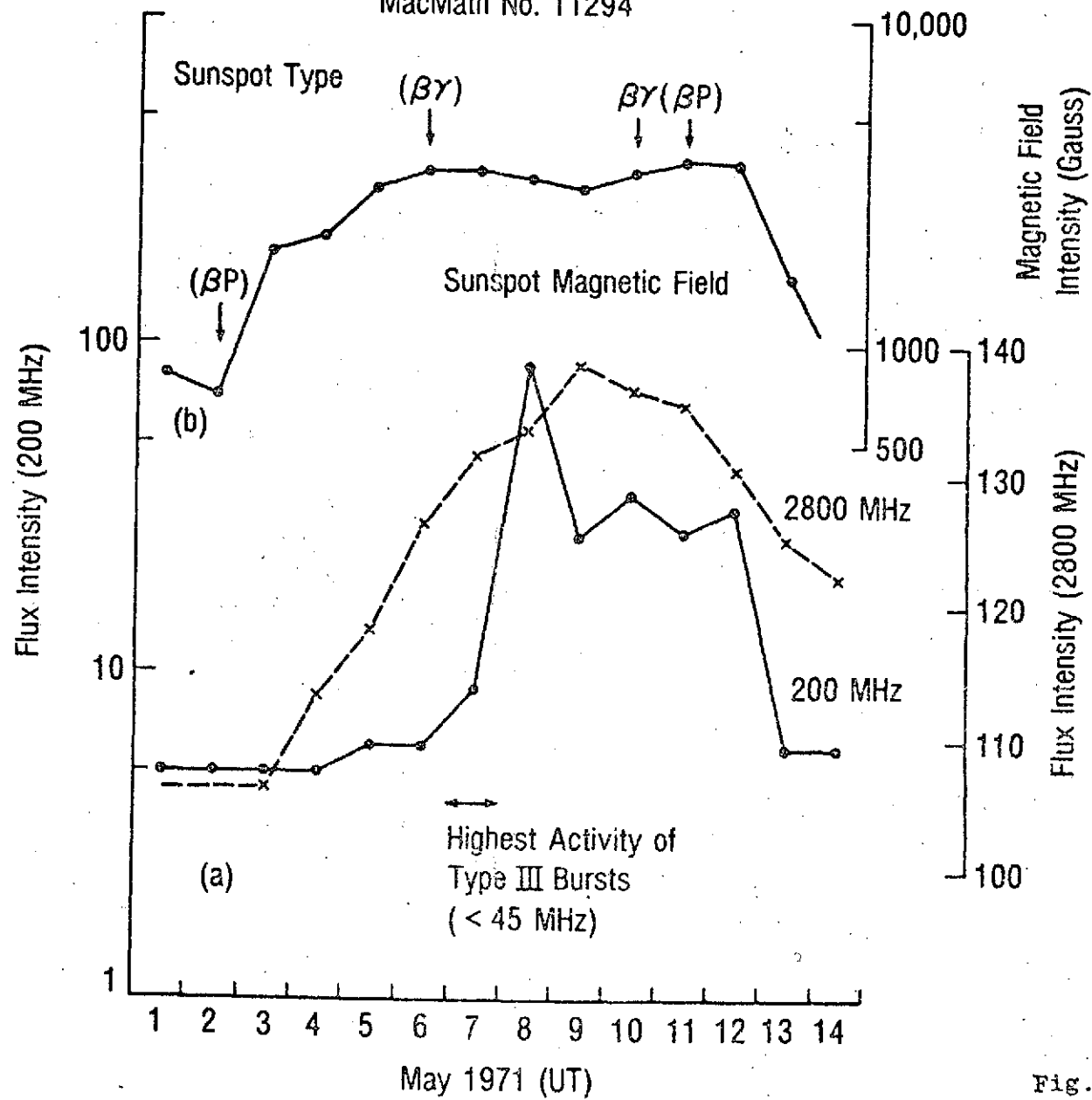


Fig. 1

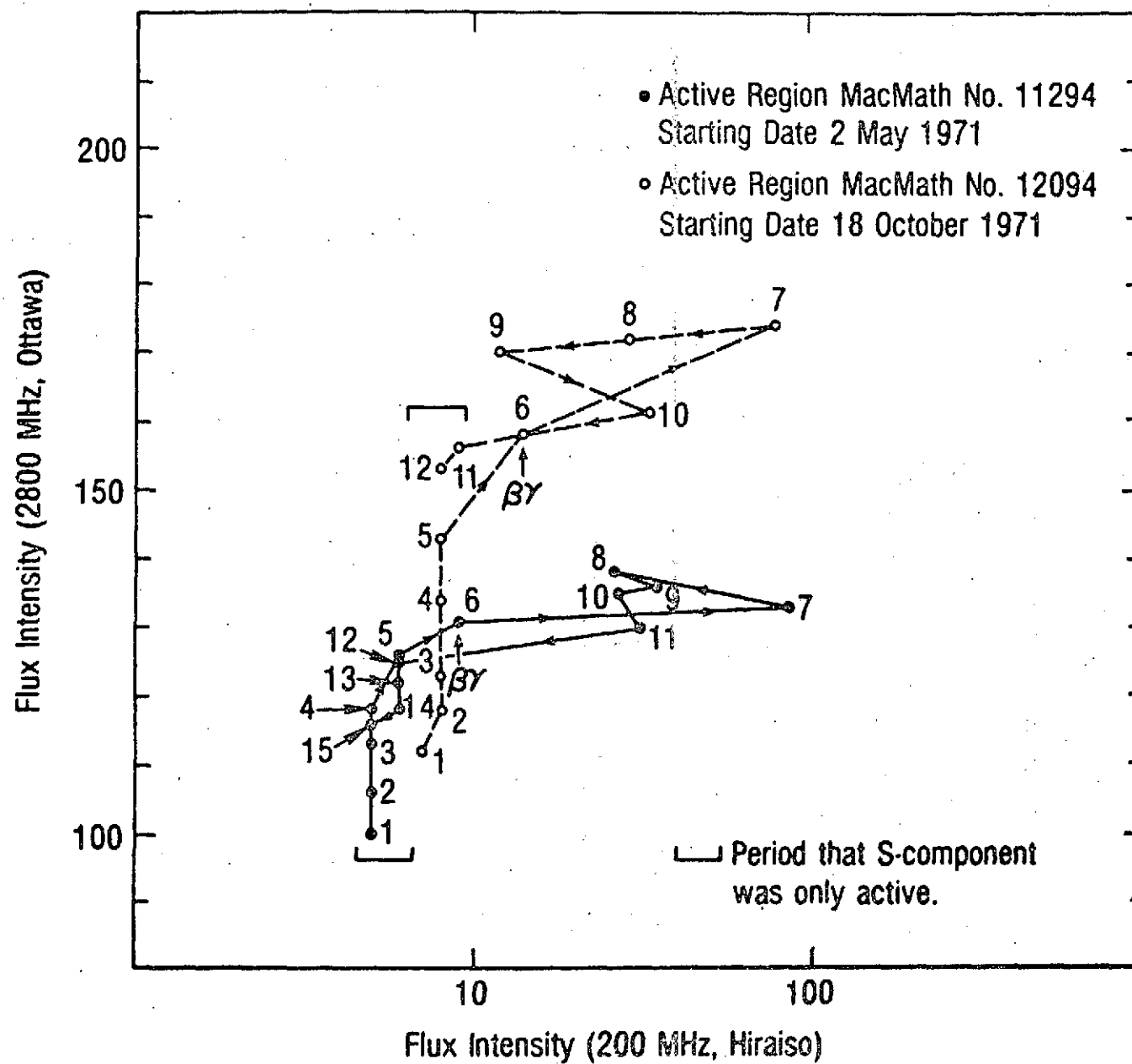


Fig. 2

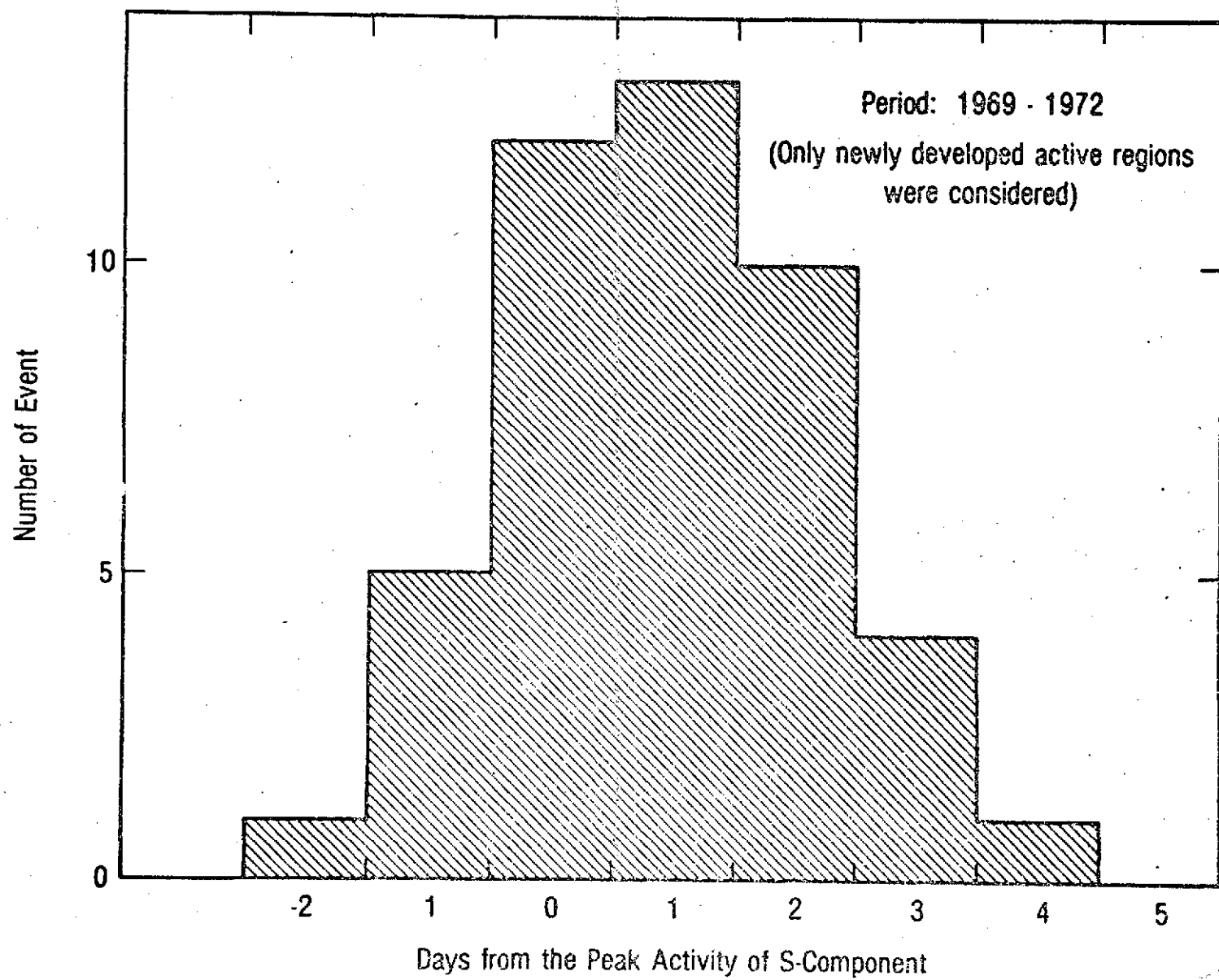


Fig. 3

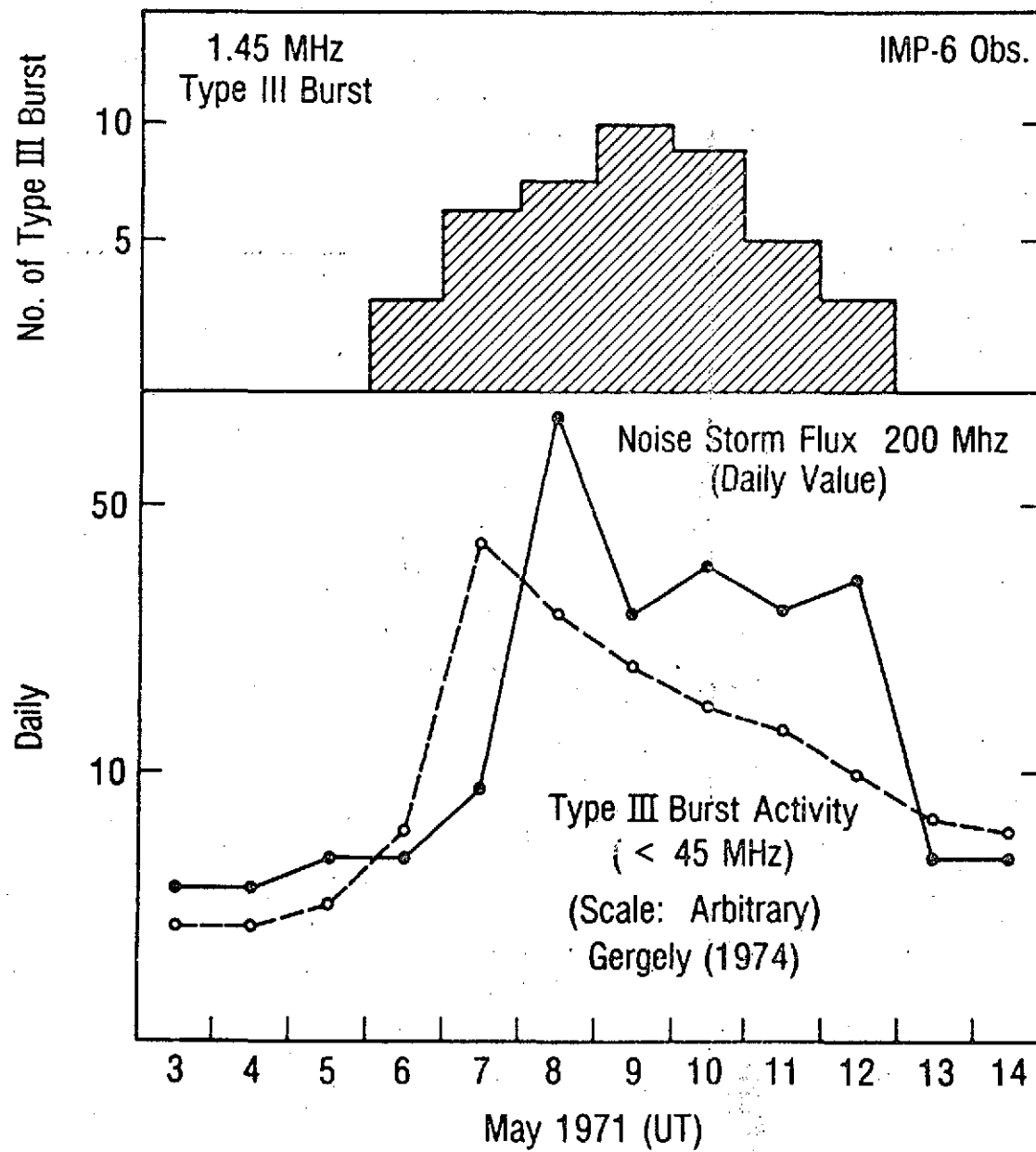
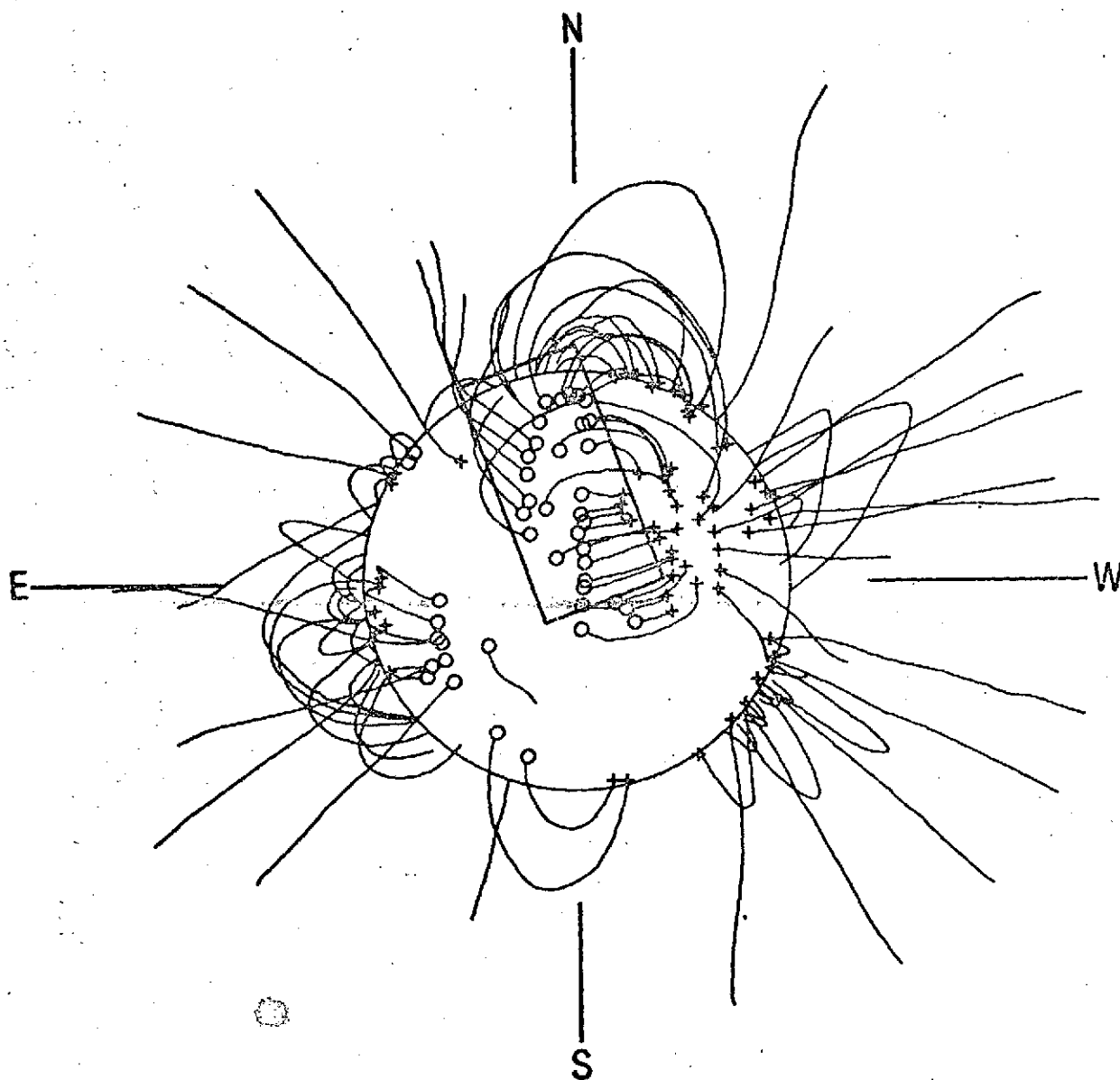


Fig. 4



Date 7,6 May 1971  
Decametric Radio Continuum Source  
indicated by a rectangle

Fig. 5



**I: TYPE I  
ACTIVE REGION**

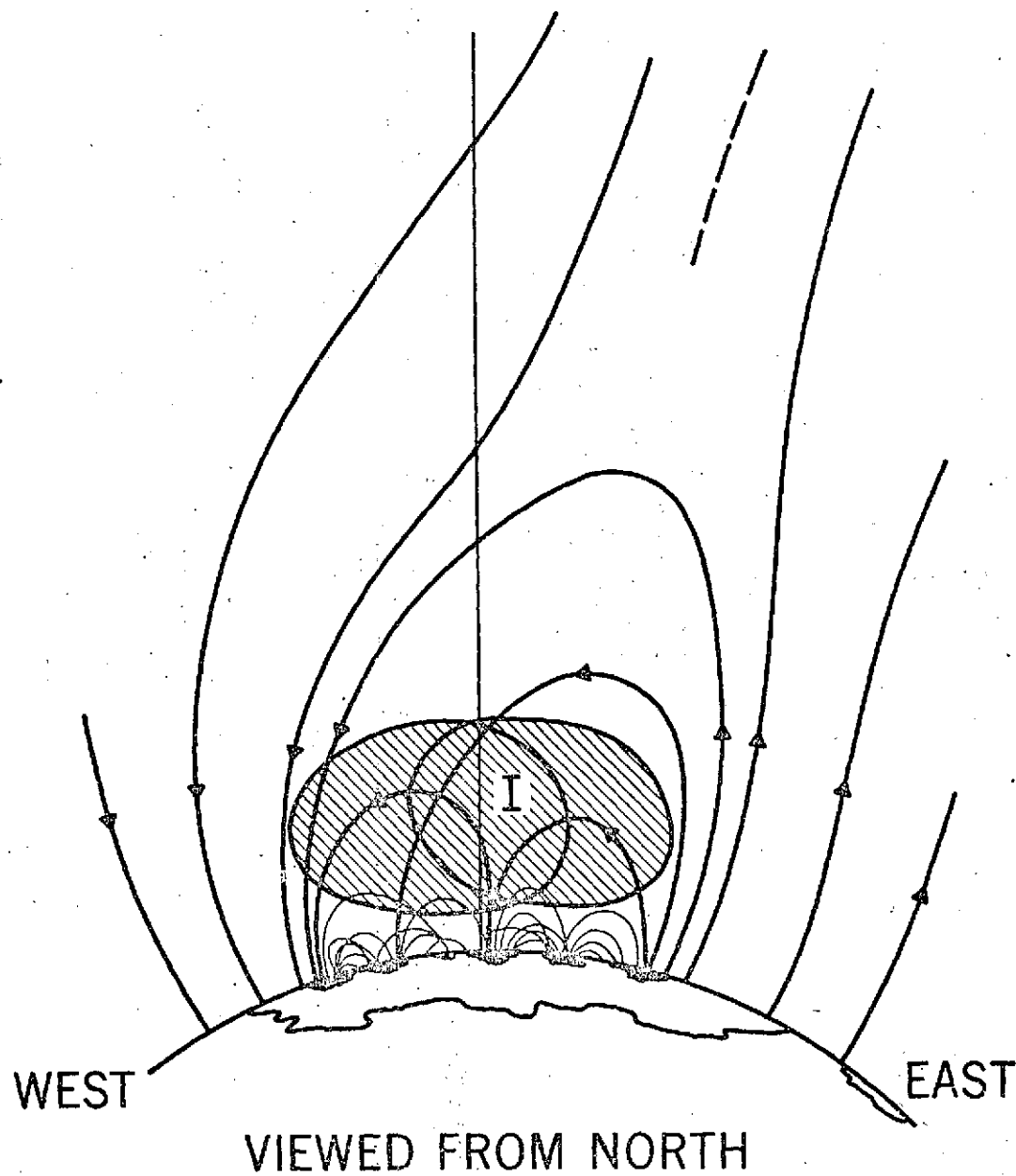


Fig. 6

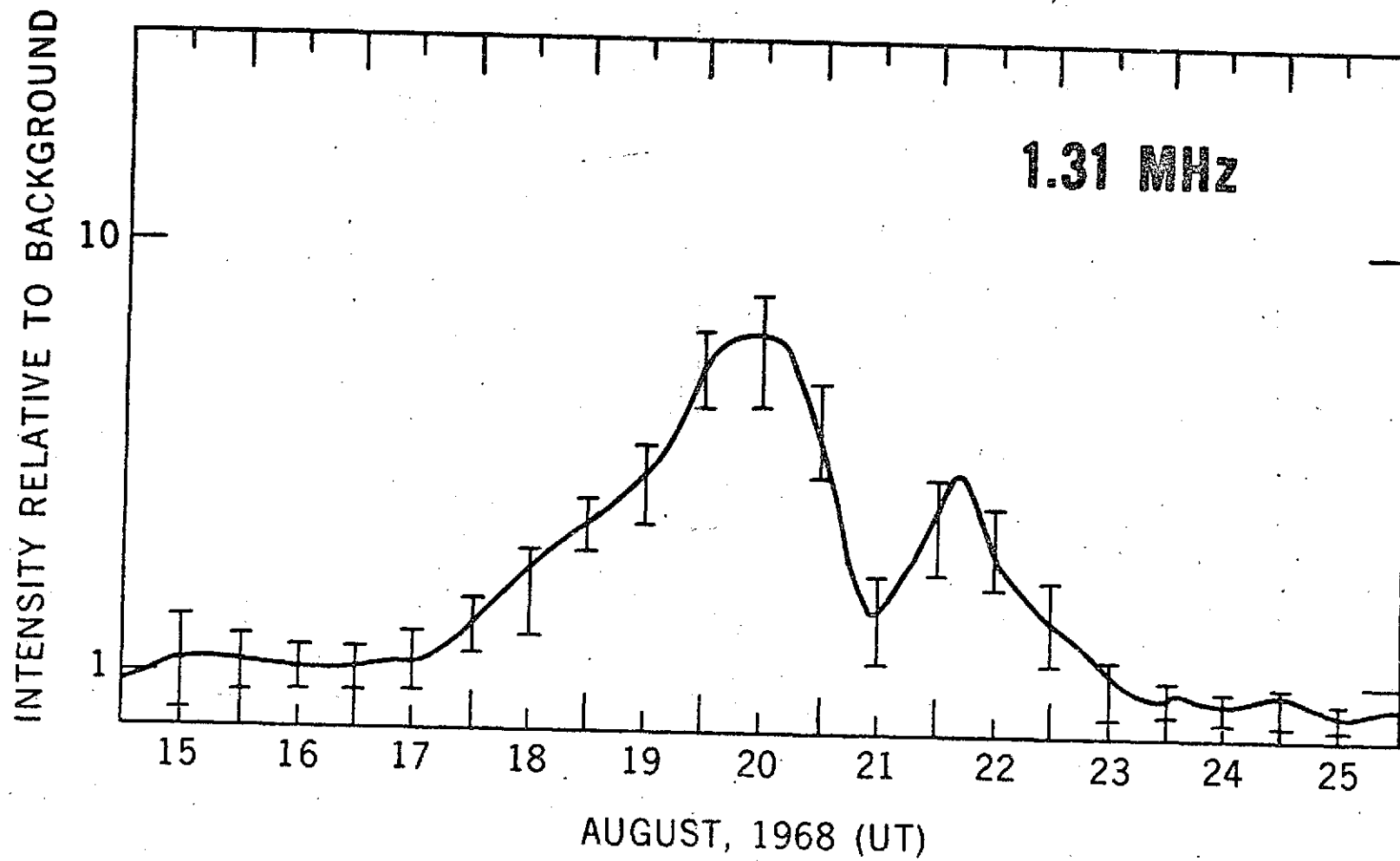


Fig. 7(a)

# BI-HOURLY MEAN VALUES OF POWER FLUX AT 200 MHz (HIRAISO)

UNIT:  $10^{-22} \text{Wm}^{-2} (\text{c/s})^{-1}$

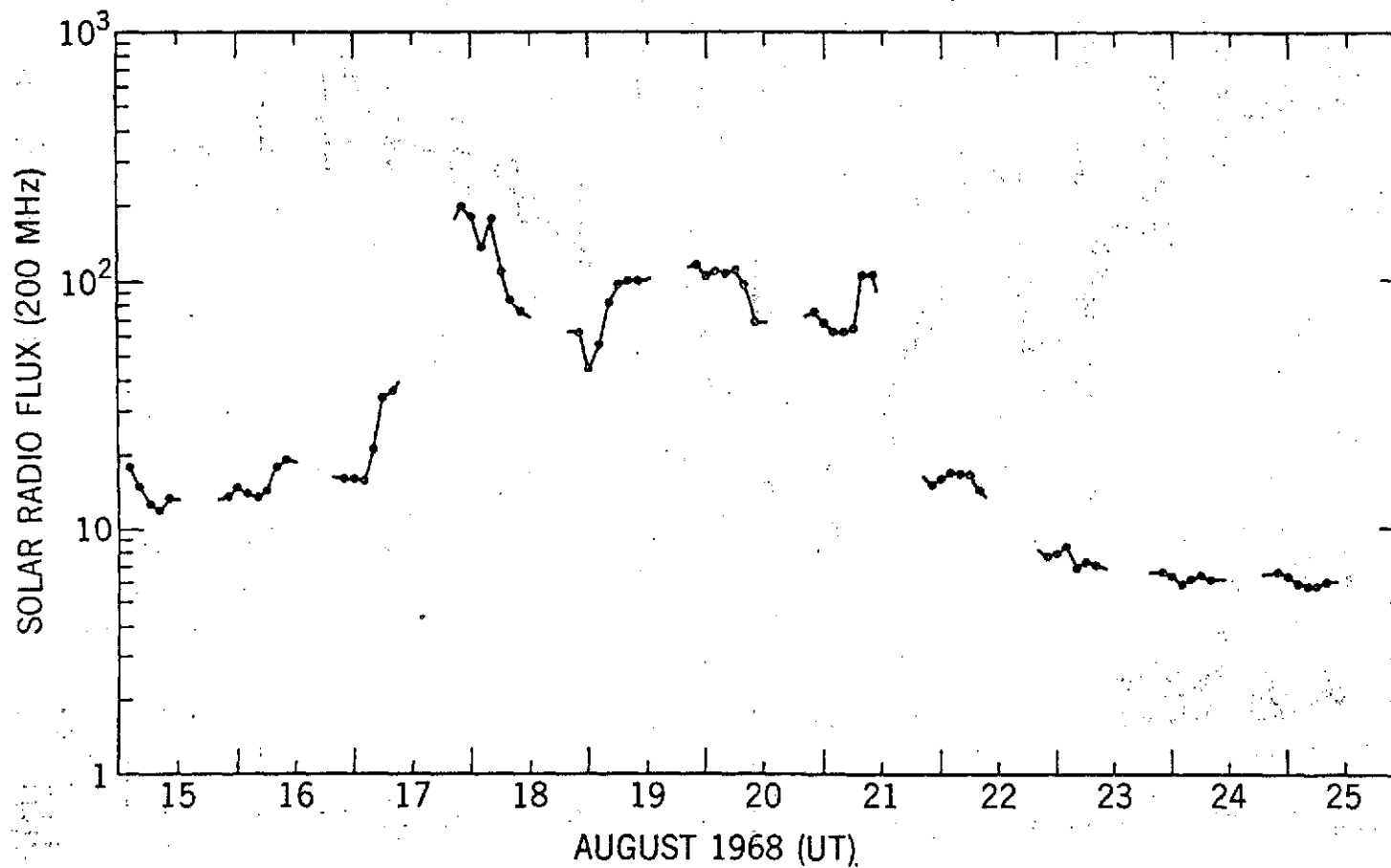


Fig. 7(b)